Driving Down Emissions

The Potential of Low Carbon Vehicle Technology





Luca Lytton

March 2010

RAC Foundation

The RAC Foundation for Motoring explores the economic, mobility, safety and environmental issues relating to roads and the use of motor vehicles, and campaigns to secure a fair deal for responsible road users. Independent and authoritative research for the public benefit and informed debate are central to the RAC Foundation's standing.

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Foreword

Whatever the scepticism and uncertainties about climate change in the minds of the public, the UK government is committed through the Climate Change Act to a wide and prolonged programme of action to reduce greenhouse gas emissions by 80% by 2050. A shorter term goal is to cut emissions by a third by 2020.

The surface transport sector will need to play its part in achieving these reductions and while policies aimed at changing drivers' behaviour have their parts to play, the current emphasis of government is on the greening of private and commercial vehicles through advances in technology. The Department for Transport, the automotive industry, and a range of other organisations are increasingly engaged in the urgent need to limit carbon emissions. The battle is being fought on various fronts: through the improvement of conventional powertrains; the further advancement of hybrids; the development and rollout of all-electric vehicles; and continuing research into hydrogen and biofuels.

The RAC Foundation believes climate change, and the availability, cost and environmental credentials of energy, are issues of vital importance to the road using public. The price of fossil fuels for vehicles may rise substantially over the coming years as global demand for oil begins to exceed economical supply, and the possible introduction of new carbon taxes might push the price higher. A shift away from a reliance on petrol and diesel will not only be good for the planet but will also help to retain the personal mobility so many of us rely on. It is for these reasons that the Foundation has a close interest in the development, delivery and mass market availability of practical low carbon vehicles.

This report forms an important part of our continued contribution to this area of public interest and concern: it sets out the landscape of current activity and describes the varying technological routes being followed. The report also identifies challenges that will be encountered along the way.

The RAC Foundation is committed to maintaining its interest in the greening of transport and increasing its knowledge about the subject. Our independence allows us to support public policy where appropriate and to ask difficult but important questions when necessary.

Stephen Glaister

Professor Stephen Glaister
Director
RAC Foundation

Executive Summary

It is now widely accepted that human activities are contributing to and accelerating the pace of climate change through the release of greenhouse gases (GHG), predominantly carbon dioxide (CO_2), into the atmosphere. To help avoid the worst impacts of climate change, the UK government has pledged through the Climate Change Act to cut greenhouse gas emissions by 80% by 2050 relative to 1990 levels.

In the UK, a quarter of all CO_2 emissions come from transport: 90% of this originates from road vehicles. Although partially offset by improved fuel efficiency, increasing demand for car travel has led total emissions from motor vehicles to rise by 7% over the past two decades, and forecasts predict average yearly traffic growth of 1.3% until 2025. Despite this background, it is considered that in the long term road transport emissions can be cut significantly if electricity generation is decarbonised.

Reducing transport emissions through technological shifts is not only relevant to climate change, but also impacts on energy security and prices. With most analysts suggesting that peak oil production will be seen by 2030, and possibly well before, few people doubt the pump prices of petrol and diesel are set to increase substantially, and any extension of green taxes is likely to push the price up further still. As the vehicle fleet becomes more fuel efficient and less reliant on petroleum through the use of alternative fuels, motorists can be partially protected from rising costs whilst meeting their environmental obligations and continuing to enjoy the benefits of mobility.

It is clear there is further scope for decreasing CO_2 emissions by improving the efficiency of the internal combustion engine and reducing the weight of vehicle components. These improvements have a number of advantages: the skills base already exists, the manufacturing infrastructure is in place and the costs passed on to the consumer will be comparatively low. However, there are technical limits to the CO_2 savings that can be achieved through improving conventional vehicles, and further progress will require changes in the vehicle purchasing decisions and driving patterns of consumers.

Electrification of the vehicle fleet provides significant opportunities for decarbonising transport. Hybrid vehicles, which combine an internal combustion engine with the ability to capture and re-use otherwise wasted energy, provide a good mix of conventional propulsion and battery technology. While emission savings of up to 50% are achievable, vehicles are still very similar in style to conventional cars and do not suffer from limited range. Grid-connected electric vehicles potentially offer very low emissions if electricity generation is decarbonised. However, limitations in battery technology and ‘diseconomies’ of scale currently make these vehicles several thousand pounds more expensive than their conventional counterparts, creating a barrier to mass market introduction. The difficulties of providing the appropriate infrastructure for grid-connected electric vehicles with zero or low carbon emissions will need to be overcome too.

Other alternative fuels also promise much in terms of CO_2 reductions. Biofuels, especially advanced ones produced from waste and residues, offer significant greenhouse gas savings when based on a complete lifecycle, but only if they do not result in direct or indirect land use change or significant GHG emissions from cultivation and transportation. Questions remain about whether biofuels might be better employed in aviation or other sectors of the economy rather than road transport. Hydrogen, despite offering zero tailpipe emissions, is at a fairly early stage of development. The cost of vehicles, infrastructure and the sustainability of hydrogen production present complex challenges.

It is unlikely that any single technology can deliver the carbon reductions required from the transport sector. Each could have a significant contribution to make, but at different points in time. In the short term, targets have the best chance of being met through the optimisation of conventional cars. The medium to long term will most likely see a gradual take up of advanced hybrid and fully electric vehicles, with their rollout starting in the urban environment. These are likely to be followed by biofuel and hydrogen powered cars, though it has yet to be proved that such fuels will be sustainable in economic and environmental terms.

There are also big uncertainties surrounding the attitude and purchasing behaviour of consumers in the market place; providing incentives to motorists to choose low carbon vehicles is essential. Financial inducements geared towards lower emission vehicles, subsidies for car purchase or scrappage, grants for research and development, and infrastructure provision are among the many policy and levers available to government to incentivise popular adoption of new technologies. But consumer behaviour is not simplistic and much more work is needed on how best to stimulate the demand side of the low carbon vehicle market.

The role of government at this stage is complex and subtle. Promising ideas should be encouraged without distorting the market or stifling market-led development, and policy decisions need to be taken not just at a national level, but on an international basis. It is also crucial that incentives aimed at encouraging take up are financially sustainable and appropriate. The government’s recent commitment to substantial grant programmes supporting both consumer uptake of low carbon vehicles and the provision of a charging infrastructure for electric vehicles is an important start but with the scheme set to run only until 2014, subsequent plans to encourage take up will have to be considered carefully.

The RAC Foundation regards the greening of road transport as crucial for two reasons.

Firstly so motorists can play their part in tackling climate change, and secondly to protect personal mobility which is so important to the economic and social wellbeing of the nation.

The challenge is not only to stimulate both the supply and demand side of the low carbon vehicle market, but to make sure progress on each happens in tandem. It will not be easy but it must be done.

1. Introduction

Although scepticism and uncertainty remain, it is now widely accepted that human activities are contributing to and accelerating the pace of climate change through the release of greenhouse gases (GHGs), carbon dioxide (CO_2) in particular, into the atmosphere.[1] In order to avoid adverse impacts for future generations, global warming must be limited to no more than 2 degrees centigrade, which according to modelling by the International Panel on Climate Change (IPCC) would require GHG emissions reductions of at least 80% by 2050 relative to 1990 levels (Metz et al., 2007).

Countries around the world have committed to GHG reduction targets to help meet this challenge. Following the conclusions of the IPCC (ibid.) and the recommendations of the Stern Review (HM Treasury, 2006) on the economics of climate change, in 2008 the UK passed the Climate Change Act setting the country's GHG reduction target at 80% by 2050 relative to the 1990 baseline. Meeting this target will be extremely challenging since emission reductions tend to come at a high price. The recent global economic downturn has resulted in government worldwide facing difficult choices between climate change and energy security imperatives.

For transport, this tension is intensified by the fact that over the past century motoring has become one of the major drivers of the economy. Transport systems move people, goods and services, and are therefore central to any country's prosperity. Contrary to popular belief, the UK has a high share of low-income motorists who rely on the car to go about their daily business (Bayliss, 2009). On average, families with a car spend 14% of their disposable income on transport, the majority of which is spent on cars (ONS, 2009). The figures are even higher for lower income families.

The crucial question that arises is how road transport can be decarbonised in order to mitigate climate change whilst at the same time not only acknowledging the role of the car in the economy, but also easing economic pressures on families across the country.

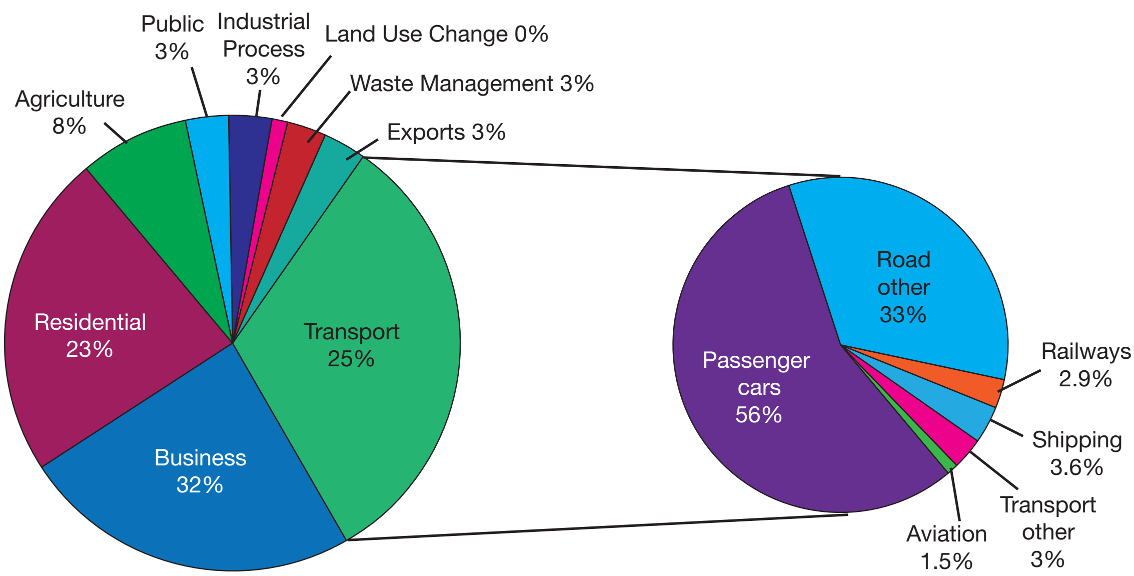
It is precisely against this background that this position paper on low carbon vehicle technologies must be seen. By simultaneously offering substantial emission reductions and catering to the mobility needs of the population, low carbon vehicles may have the potential to bridge the gap between climate change imperatives and individual mobility. Given the economic context, however, it is essential that the most cost-effective and environmentally beneficial solutions are found.

1 Further GHGs include methane (CH_4), nitrous oxide (NO), hydro-fluorocarbons (HFC), perfluorocarbons (PFC) and sulphur hexafluorides (SF_6) (ONS, 2010).

2. UK Policy Background

Before providing an overview of the policy background regarding low carbon vehicles, it will be useful to understand the sources of CO_2 emissions in the UK. As Figure 1 illustrates, the main sources are energy supply (e.g. electricity generation), business, industry, residential, agriculture and transport:

Figure 1 UK GHG emissions by end/final user in 2008 measured in CO_2 equivalents[3]



Source: based on data from ONS (2010)

In 2007 (the latest available figures for end/final user) domestic transport accounted for 24.5% (156 million tonnes) of all CO_2 emissions by end/final user in the UK.[2] Road transport represented almost 90% of transport CO_2 emissions, with passenger cars alone making up 56%, or 13.8% of the UK's total domestic CO_2 emissions. Heavy-goods vehicles are responsible for the second largest share of road transport emissions at 19% and are

[2] Providing emissions data by end/final user rather than by source is more appropriate, as they take into account the redistribution of emissions from power stations and other fuel processing industries to the sector that actually uses them (DfT, 2009a).

[3] Emissions are often measured in CO_2 'equivalents', which refers to the global warming potential of the five other GHGs. While methane, for example, is 21 times more potent a GHG, nitrogen oxide is actually 380 times more damaging (ONS, 2010).

projected to increase further in the future. These figures would, however, be lower if international aviation and shipping were included: in 2007, all aviation contributed 19.2% to all transport emissions, while road transport accounted for 70%, with passenger cars making up 44%. However, as there is no internationally agreed way of reporting these emissions they are excluded from the calculations (DfT, 2009a).

Demand for car travel increased by 20% between 1990 and 2007 (CCC, 2009a). Even though this increase in demand has been slightly offset by the falling carbon intensity of new cars from just over 200 grams of CO_2 per kilometre (gCO_2/km) to 149.5 gCO_2/km today (SMMT, 2010), total emissions from cars have still increased by 7% (CCC, 2009a). This has important future implications as demand for transport is expected to grow by over 30% until 2025 relative to 2003 levels (DfT, 2008). Experts estimate that if current trends continue at business-as-usual levels, transport alone will exceed the UK's 80% emissions reduction target. Even in the International Energy Agency's highly ambitious Blue Map scenario with an 80% market share of low carbon vehicles (IEA, 2009), transport alone would account for the entire 80% carbon budget.[4]

Table 1 Vehicle excise duty (VED) for cars registered on or after 1 March 2001

Band	CO_2 emissions (g / km)	Standard rate 2009-10* (£)	Standard rate 2010-11* (£)	First-year** rate 2010-11* (£)
A	Up to 100	0	0	0
B	101-110	35	20	0
C	111-120	35	30	0
D	121-130	120	90	0
E	131-140	120	110	110
F	141-150	125	125	125
G	151-165	150	155	155
H	166-175	175	180	250
I	176-185	175	200	300
J	186-200	215	235	425
K***	201-225	215	245	550
L	226-255	405	425	750
M	Over 255	405	435	950

* Alternative fuel discount: 2009-10, A-I £20, J-M £15; 2010-11 onwards, £10 all cars

** So-called 'showroom tax'

*** Includes cars emitting over 225g/km registered between 1 March 2001 and 23 March 2006

Source: HM Government (2010)

[4] Shaping a Greener Future, Decarbonising Road Transport in the UK, AWBriefing seminar, 15 October 2009.

To stimulate the purchase of low carbon vehicles the UK government in its 2006 Budget introduced a tax banding for cars according to their per kilometre tailpipe emissions, which has since been modified further as shown in Table 1. Company car tax, reformed in 2002 and linked to CO_2 emissions, is another important policy stimulus. From April 2010, electric vehicles will be tax free (down from 9%) for companies for a period of five years, which is important considering that the proportion of new registrations to companies has in recent years increased to almost six in every ten cars (DfT, 2009).

In March 2007, the UK government set up the King Review lead by Professor Julia King, Vice-Chancellor of Aston University, to investigate the vehicle and fuel technologies that, over the next 25 years could help to decarbonise road transport (HM Treasury, 2007; 2008).

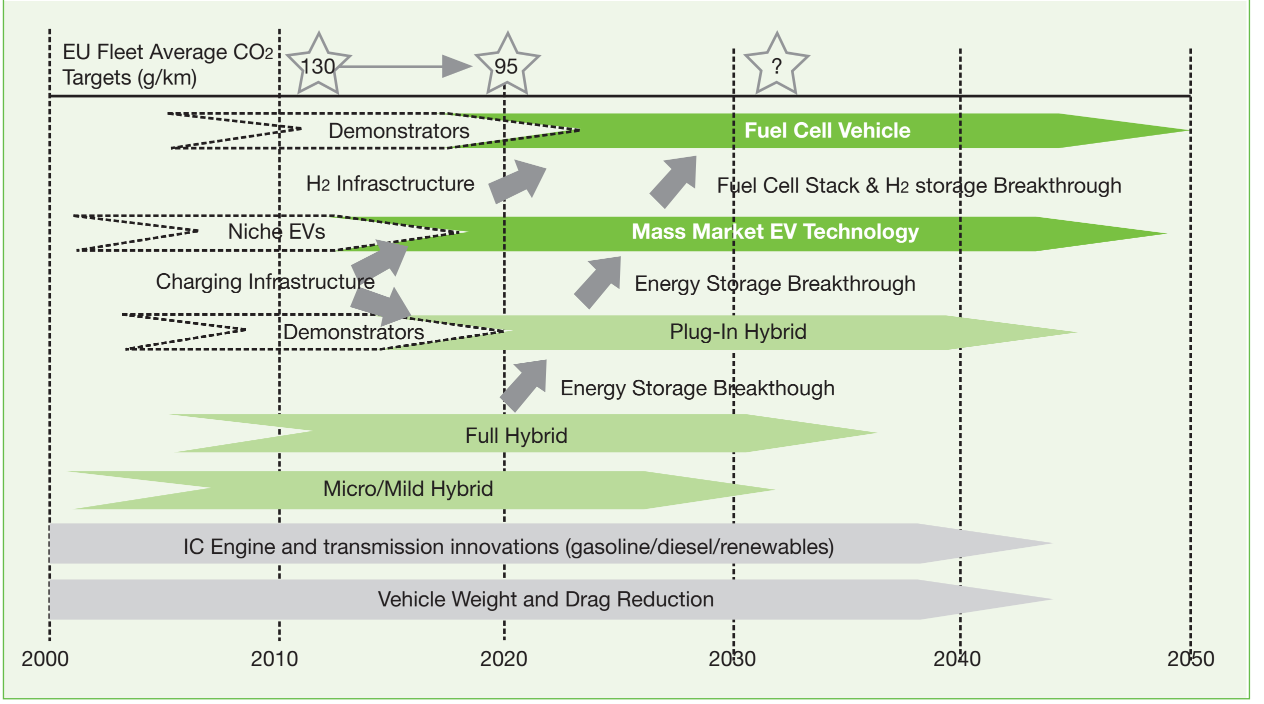
The first report (HM Treasury, 2007) concluded that in the long term an 80% reduction in emissions from road transport was feasible even with increasing traffic demand; if the power sector as decarbonised, per kilometre emissions could be decreased by 90% to less than 15 gCO_2/km in 2050. In the medium term to 2030, emissions per vehicle could be halved relative to 2000, thereby reducing net emissions from road transport by almost a third after taking increases in the demand for transport into account. Although biofuels are likely to have a moderate role to play, and conventional vehicles could be optimised to achieve 30% efficiency improvements in the short term, the most promising long-term solution to truly green road transport is electrification with a decarbonised power sector.

The second part of the King Review (HM Treasury, 2008) made 40 specific policy recommendations which included the introduction of: ambitious per kilometre, emissions standards; measures to ensure sustainable biofuels; demand-side policies such as consumer incentives and information campaigns to encourage an uptake of low carbon vehicles; increased R&D efforts through, for example, the Technology Strategy Board; and better cross-governmental coordination.

In April 2008, following the recommendations of the King Review, the UK government launched the New Automotive Innovation and Growth Team (NAIGT), an industry led steering group of senior industrialists, academics and financial analysts experienced in the automotive sector. Its aim was to devise a 20 year vision for the future of the UK automotive industry. Central to this vision was the development of a vehicle technology roadmap (see Figure 2).

The roadmap shows a gradual shift towards the electrification of vehicles, starting with hybrid technologies and aiming for fuel cell and hydrogen vehicles. Alongside these developments it is expected there will be improvements to the conventional international combustion engine and overall downsizing of vehicles will take place to reduce weight and drag. In order to facilitate this shift, the NAIGT called for the establishment of a joint industry/government Automotive Council to facilitate the development and implementation of a long-term strategic framework for the UK automotive industry. Following the advice of the NAIGT, the government set up the new Automotive Council at the end of 2009.

Figure 2 NAIGT Roadmap



Source: NAIGT (2009)

In early 2008, the then Department for Business, Enterprise and Regulatory Reform (BERR, now Department for Business, Innovation and Skills, BIS) and Department for Transport (DfT) commissioned the Centre of Excellence for Low Carbon and Fuel Cell Technologies (Cenex) and Arup to investigate the scope for road transport to switch to vehicles powered through electricity from the grid until 2030 (BERR & DfT, 2008). The report, published in October 2008, concluded that electric and plug-in hybrid electric vehicles offer potential CO_2 reductions of 40%, even on the current UK electricity grid mix when compared to conventional petrol or diesel cars over a full life cycle. In order to achieve a widespread rollout of electric vehicles after 2014, the report made the case for infrastructure development and market stimulation through the use of monetary incentives that compensate for the higher costs incurred by the purchase and operation of electric vehicles.

Recognising the relative failure of the 1998 ACEA agreement[5], the EU Council of Ministers and European Parliament adopted a regulation[6] in April 2009 setting binding per kilometre CO_2 emission standards for vehicle manufacturers in the EU. The regulation stipulates that by 2015, the EU new car fleet must average 130 gCO_2/km with a longer-

[5] The ACEA (European Automobile Manufacturers' Association) agreement set a voluntary target of 140 gCO_2/km to be met by vehicle manufacturers by 2008. In 2009, however, the EU new car fleet averaged 153.5 gCO_2/km (European Commission, 2009).

[6] Regulation 443/2009; http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0001: 0015:EN:PDF

term target of 95 gCO_2/km in 2020. A technology neutral policy instrument, the regulation aims at encouraging the improvement of existing vehicle technologies but also new technologies through eco-innovation.

In order to ensure compliance with the standards, each vehicle manufacturer is given an individual target and penalties for non-compliance. Until 2018 the penalty will be €5 for each car sold for the first gCO_2/km above the target, €15 for the second, €25 for the third, and €95 for each subsequent gCO_2/km over the target. From 2019 each gCO_2/km over the target will be penalised with €95 per car. To make the targets feasible, vehicle manufacturers will be able to earn 'super-credits' until 2015 whereby vehicles emitting less than 50 gCO_2/km are counted as more than one vehicle towards meeting the target.

After the adoption of the EU Directive, the DfT issued a strategy on low carbon transport in July 2009, which set out how the UK was to reduce emissions from transport by 32.7 million tonnes of CO_2e ($MtCO_2e$) against the business-as-usual scenario by 2020 (DfT, 2009b). The principal ways in which this will be achieved is through supporting a shift to new technologies and fuels, promoting lower carbon choices and the use of market mechanisms to encourage such a shift. In order to achieve these targets, the UK government has now committed a total of £400 million towards the development and uptake of low carbon vehicle technologies (HM Government, 2009; DfT, 2009e).

In October 2009, the Committee on Climate Change (CCC), an independent advisory body established under the Climate Change Act to advise the UK government on its climate change policy, issued its report on meeting the UK's carbon budgets for the period up to 2022 (CCC, 2009a). By 2020 it estimates that overall transport emissions could be reduced by up to 32 $MtCO_2e$ "with most of the reduction potential coming from road transport" (ibid.: 189). Until the end of the third carbon budget in 2022, direct emissions from road transport would have to decrease by 29% relative to 2007 levels, and make up a fifth of the UK's overall CO_2 savings.

One of the main ways the CCC envisages this CO_2 reduction taking place is through advances in vehicle technology. The widespread penetration of electric vehicles into the overall car fleet is seen as central to this, and it is claimed that through pilot projects and incentives the number of full electric vehicles could amount to 240,000 in 2015, and 1.7 million by 2020.

Further commitments for the promotion of low carbon vehicles include the Infrastructure Grant Programme (IGP) provided by the DfT. Through the IGP, companies are able to apply for grants in two rounds during 2010. These will be made available to encourage them to install refuelling/recharging stations for alternative fuels. Funding will be made available for hydrogen, natural gas and biogas, as well as electricity.

The UK is not alone in its ambitions to decarbonise road transport through an uptake of low carbon vehicle technologies. Other member states of the EU have adopted similar policies: Spain has committed a budget of €245 million to stimulate a rollout of one million electric vehicles by 2014; France has committed €400 million for the development of electric vehicle infrastructure with the help of Electricité de France and Renault; and Germany is planning to deliver one million electric vehicles by 2020.[7]

[7] Electric Vehicles at the Crossroads: Towards a Comprehensive EU-Wide Approach, AWBriefing conference, 18 February 2010.

3. Technological Options

Motorised vehicles can be decarbonised in three principal ways: building on and improving existing internal combustion engine based technology; electrification, including hybridisation; and using low carbon fuels, the most promising being biofuels and hydrogen. The aim of this section is to provide an overview of the opportunities and challenges, and to outline government policy related to each of the options.

There are certain key concepts that need to be understood before looking at each technology option in turn. These are:

- Well-to-wheel: This refers to the pathway from the source of energy to the delivery of the energy at the wheel. It comprises well-to-tank and tank-to-wheel energy /emissions.
  - Well-to-tank: Well-to-tank is the path from the source of energy to the point of fuelling.
  - Tank-to-wheel: This is the pathway from a vehicle's energy storage to the wheel. Tank-to-wheel emissions are also known as emissions 'at the tailpipe'.

The above concepts can linked with energy efficiency and GHG emissions, but do not take into account manufacturing and scrappage or recycling.

- Fuel consumption: This refers to the amount of fuel that is required to run a vehicle over a certain distance, and is normally expressed in litres per 100 kilometres (L/100km).
- Fuel economy: This is the distance a vehicle can run on a certain amount of fuel, usually expressed in miles per gallon (mpg).

3.1 Optimising conventional cars

Thanks to the co-evolutionary nature of certain developments in the early 20th century, the internal combustion engine (ICE) has been the dominant and largely unrivalled form of automotive propulsion for almost a century. Amongst these developments were the invention of the assembly line by Henry Ford which enabled the mass production of cars, the availability of cheap oil and the alignment of several sectors of the economy with the car industry (oil, steel, infrastructure, services, etc.), the strategic backing of the automotive industry by the state and the relative weakness of the ICE vehicle's main competitor, the electric vehicle. Virtually all (99%) motorised vehicles today are based on the same paradigm as in the early-mid 20th century: a multi-purpose, all-steel vehicle that is propelled by an ICE (HM Treasury, 2007).

Although it has become much more sophisticated over time, the spark ignition ICE still functions in much same way as it did almost a century ago: petrol is mixed with air, usually by a process of fuel injection, and the mixture is drawn into a combustion chamber (the cylinder) through a valve, where it is compressed to reach high temperature. The combustion process is then initiated by a spark plug which causes the gas to expand, thereby forcing the piston to move, doing work that is transmitted to the wheels through the powertrain. In diesel engines the combustion is caused by the high temperature that results from the compression process. The combusted gases subsequently leave the combustion chamber as exhaust fumes, most notably CO_2, water (H_2O) and nitrogen (N_2), through another valve so that the process can start again.

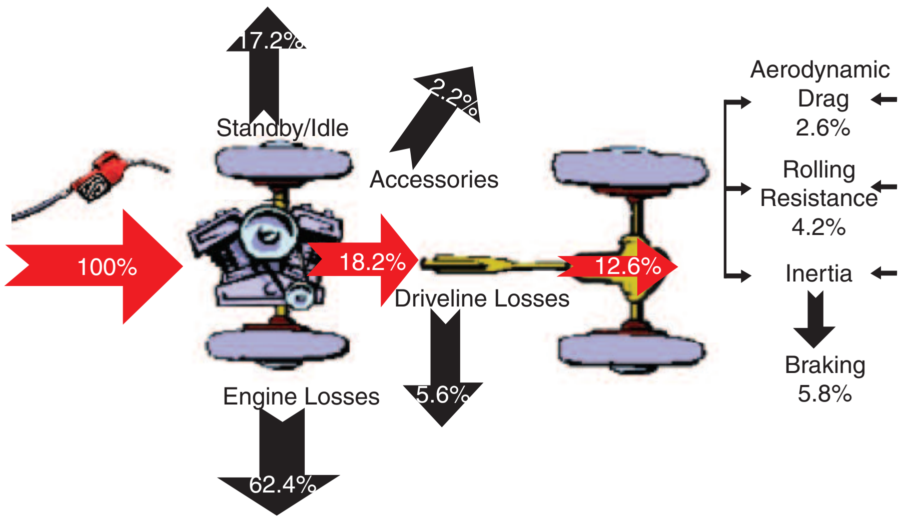
In optimum conditions the combustion of one litre of petrol produces 2.30 kgCO_2 at the tailpipe, and 2.63 kgCO_2 in the case of diesel (DEFRA, 2009). Hence the more fuel efficient the vehicle, the less petrol/diesel is consumed per mile and the less exhaust fumes (including CO_2) are emitted.

3.1.1 Opportunities

Despite their maturity and the continuous advancements being made, there are still several areas of improvement for ICEs' energy efficiency that have not yet been fully explored.

Figure 3 depicts the main sources of energy losses from an ICE vehicle. Although the figures are only indicative and vary from vehicle to vehicle, it shows that a major part of the energy entering the vehicle is lost through the engine due to friction, pumping, waste

Figure 3 Principal sources of energy losses from a petrol engine vehicle



Source: US DoE (2010a)

heat and idling. Further losses are caused by parasitic losses from accessories, and from the transmission (i.e. from delivering the mechanical energy created by the engine to the wheels) due to the number of rotating elements which incur friction losses. Ultimately, only a fraction of the energy that enters the engine is actually used to propel the vehicle forward.

The main areas of conventional vehicle improvement involve the engine and transmission, as well as reducing weight and downsizing. Smaller improvements can be achieved through reduced drag and rolling resistance.

There are several options to reduce energy losses from the engine, as shown in Table 2. According to E4tech (2007) every 2% reduction in engine capacity will increase its efficiency by 1% through reduced waste potential, with an overall conceivable improvement of 40%. The improvements are not additional in all cases but, taken together, could deliver reductions in the order of 15 to 30% by 2020 (HM Treasury, 2007).

Table 2 Areas of improvement for ICE-based vehicles

Technology	Efficiency saving (%)	Cost per vehicle (£)
Variable valve actuation	3-7	175-250
Direct fuel injection and lean burn	3-13	175-250
Cylinder deactivation when not in use for larger vehicles	6-8	N/A
Downsizing engine capacity through turbo- or supercharging	3-15	150-300
Components with reduced friction	3-5	Negligible
Homogeneous charge compression ignition (HCCI)	17	N/A
Improved transmissions (automated manual transmissions; dual clutch; continuously variable transmissions)	1-7	400-600
Regenerative braking through flywheels*	30	N/A
Lightweighting	10	250-500
Advanced water cooling	1.5-3	N/A
Improved electrically assisted steering	2-3	N/A
Low rolling-resistance tyres	2-5	50-100

* Flywheels are a mechanical form of regenerative braking whereby the kinetic energy generated by braking is stored in a wheel and reused in the transmission when necessary. One of the companies currently developing this technology is Flybrid Systems (http://www.flybridsystems.com).

Source: figures based on E4tech (2007); GFEI (2009); HM Treasury (2007); MacKay (2008); DoE (2010b)

Substantial increases in fuel efficiency could be achieved through the improvement of thermal efficiency, i.e. the ratio of fuel energy consumed by the engine to the power output (cf. Figure 3). While the thermodynamic limit is around 30 to 50%, most current engines achieve 20 to 40% at their peak (E4tech, 2007). In theory, this could be doubled by recovering the waste heat lost through the exhaust and cooling systems. Technological options include the use of thermovoltaic cells or heat engines using the Stirling or bottoming cycles, which could recover about half of the energy dissipated as heat (ibid.) but are technically complex and expensive to develop.

Another option would be to encourage an uptake of more fuel efficient diesel engines, though this would give rise to health issues which will be discussed later. In 2008 the fuel economy of the average petrol car was 31 mpg, compared to 38 mpg for the average diesel car; for the average *new* car the respective figures were 40.73 mpg for petrol and 47.29 mpg for diesel (DfT, 2009d). The average diesel engine was thus 20% more fuel efficient than its petrol counterpart. Although petrol-based cars are expected to close the efficiency gap within the next couple of years, further improvements in diesel engines are expected through higher pressure combustion processes, more precise fuel injection systems and improved exhaust circulation through advanced turbocharging (E4tech, 2007).

As the GFEI (2009) estimates, cutting the global average car fuel consumption by half would reduce emissions by 1 GtCO_2e by 2015 and over 2 Gt by 2050, or 2.4% and 4.8% of the estimated 42 Gt requirement to achieve 80% GHG emission reductions (Jha, 2009).

The second major area of improvement, which will benefit all forms of vehicle, includes reducing vehicle weight, reducing size and specifications. Reducing weight can involve either the use of new materials or using existing materials in new ways. As the heaviest single component in a vehicle is the body shell, making up about a third of total weight, large savings can be achieved only by reducing the mass of many components (E4tech, 2007). The most promising options are the use of new grades of high strength steel and increased use of aluminium. While it is viewed that steel can further be optimised to deliver up to 20% weight reduction, aluminium is – albeit more expensive – lighter, stiffer and stronger than steel and could be used in a greater number of components such as engine blocks and closures. It is also more attractive because it offers larger recycling potential than steel. Other options include the employment of alloys and composites, which can bring even greater weight reductions (up to 40% compared to steel) but are also less mature and far more expensive (ibid.).

According to a study carried out for the European Commission (TNO et al., 2006 in E4tech, 2007), vehicle weight reductions of 1.5% (mild), 3.6% (medium) and 9% (strong) can lead to carbon savings of 0.9%, 2.2% and 5.5% respectively for small petrol vehicles.

CO_2 savings are, however, estimated to come at a cost of around €20-40 for every mild CO_2 percentage saving, €25-50 for medium and €40-80 for strong. Put differently, mild weight reductions are cheaper but can deliver only minor CO_2 reductions; strong weight reductions are expensive, but offer more significant reductions in per kilometre CO_2 emissions.

Fuel savings can also be delivered simply by reducing vehicles' size and performance specifications. Premium cars in particular are significantly overpowered; some vehicles actually have up to five (or more) times the power needed to propel them forward. Building smaller cars with lower specifications will not only decrease the amount of energy needed at point of use, but also reduce the resources and energy required to manufacture them. These non-powertrain measures can therefore even come at a 'negative cost' (i.e. when ongoing operating cost reductions more than offset any upfront costs), as recognised by the CCC (2009a).

Finally, it is possible to reduce drag and rolling resistance through better aerodynamic design and low rolling resistance tyres, although there is a trade off to be made between potentially employing extra bodywork for improved airflow and increasing vehicle weight (E4tech, 2007).

On the whole, the highest CO_2 savings can be achieved through the deployment of several of the above options. Depending on the extent of take up, the above improvements could bring about CO_2 reductions of up to 30% by 2020. As the King Review (HM Treasury, 2007) estimates, exchanging all conventional vehicles in the UK with best in class vehicles already available in showrooms would reduce road transport emissions by 25%; this could be achieved at a cost of about £1,000-1,500 per vehicle, which would be compensated for by lower operational cost resulting from the achieved fuel savings. If 30% efficiency savings were achieved, motorists who drive 10,000 miles a year would lower their fuel bill by £300-500 (assuming a petrol cost of 9.41-15.81p per mile for most cars), which means that improvements would pay for themselves in three to five years (ibid.).[8]

3.1.2 Challenges

The improvement of conventional cars faces a number of challenges. The first challenge is environmental. Although considerable CO_2 savings can still be achieved in the short to medium term, there are theoretical and practical limits (such as the laws of thermodynamics) for CO_2 reductions of ICE-based vehicles. Vehicles based entirely on ICEs are unlikely to achieve per kilometre emissions of much less than 70 or perhaps

[8] Reducing the costs of motoring can, however, lead to a 'rebound effect' where decreasing costs lead to more demand, thereby offsetting or even negating CO_2 savings.

even 50 gCO_2/km[9], which is still far above the long-term per kilometre CO_2 emissions reduction target by 2050 as defined by the King Review. Although alternative low carbon vehicles face theoretical and practical limits too, they nevertheless offer considerably more CO_2 reduction potential.

From a local environment perspective, ICEs emit air pollutants such as nitrogen and sulphur oxides that can lead to respiratory diseases and cancer.[10] This is perceived to be a problem particularly with diesel vehicles which, even though more fuel efficient and thus less CO_2-intensive, fare worse when it comes to local air pollutants. It is for this reason that the Government's ActOnCO_2 campaign advocates the use of diesel vehicles for long distance travel, and petrol cars in cities. However, new diesel cars now emit 95% less particulate matter compared to 15 years ago (SMMT, 2009) and are expected to converge with petrol engines in terms of their air quality performance by 2015 thanks to the EU's Euro standards for local air pollutants.

Related to environmental concerns is the issue of energy security. ICE-based vehicles rely on oil, the production of which the UK Energy Research Centre estimates might peak even before 2020 (UKERC, 2009). Fewer oil reserves in less accessible locations will ultimately imply higher prices for consumers, not only in terms of vehicle fuel but also overall commodity prices.

Consumer perceptions and social concerns also stand in the way of conventional cars achieving substantial CO_2 reductions. Significant emissions savings could be delivered through smaller and less powerful cars with fewer features but, for many, cars still remain a status symbol and a sign of affluence. Even though most of the power remains unused because of traffic regulations and congestion, people might not want to give up this preference. Issues surrounding vehicle weight and performance are intensified by legislative safety requirements. Recent developments show that improvements in engine efficiency have been offset by increased vehicle weight owing to the incorporation of safety features (Kenington, 2008).[11] This creates an upward spiral: as cars get bigger, heavier and more powerful, so must safety features that are necessary for mitigating the impact of potential collisions.

[9] Safety and CO_2, LowCVP conference, 25 November 2009.

[10] Braking and tyre wear also give rise to particulate matter (PM), which will be a problem common to all types of vehicle.

[11] Cf. also Safety and CO_2, LowCVP conference, 25 November 2009.

3.1.3 Government policy

Improvements in the fuel efficiency of conventional cars are mainly driven by tax incentives and EU regulation as outlined in section 2. While the tax incentives and this year's 'showroom tax' aim at encouraging the purchase of more efficient conventional cars, legislation from the EU seeks to encourage manufacturers to develop greener and more advanced vehicles.

In terms of funding, the automotive sector benefits from R&D in materials research, and also from research provided by automotive/engineering consultancies and centres of excellence. Although there is little direct funding for the optimisation of conventional vehicles in comparison to alternative low carbon vehicle technologies, the government has nonetheless provided direct investment for some projects on advanced ICEs under the Technology Strategy Board's Low Carbon Vehicle Innovation Platform.

3.2 Electrification

To understand electric vehicle technology, a short explanation of the difference between kilowatt (kW) and kilowatt hour (kWh) is needed. While the former is a unit of specific power output of, for example, an electric motor (or consumption of machines), which is equivalent to 1.34 brake horsepower, kWh is a unit of energy equivalent to 1 kW of power expended for one hour of time.

In essence, the electrification of vehicle technology involves adding an electricity storage device (either a battery or capacitor) and electric motor to an ICE-based vehicle (hybrid) or basing the entire system on these electric devices (full electric vehicle). The electric motor (with power output measured in kW) converts electrical energy into mechanical energy, which can then be used to assist the ICE or drive the powertrain entirely on its own.

The capacity of the batteries to provide the energy for the electric motor is measured in kWh. Battery packs are made up of cells that store energy (i.e. electric current) to power the electric motor. The capacity to store electricity is determined by the cell's elementary voltage and the voltage is determined by the energy density of the chemical elements that make up the different components (cathode, anode, separator and electrolyte) of the cell. The higher the capacity the better, as more power will be available to drive the powertrain. The lower the capacity, the more cells the battery will require to power propulsion, making the battery bigger and heavier. Batteries can be used in tandem with super- or ultracapacitors which are able to capture a lot of electricity for relatively short periods of time to boost acceleration at times of peak demand.

Until recently, the main component chemistries used for car batteries were lead acid and Nickel Metal Hydride (NiMH). By providing a showcase for the use of batteries similar to those used in laptops and mobile phones, the development of the Tesla Roadster in 2006 has driven the deployment of lithium-based batteries in automotive applications. Although lithium-ion is the most common variant, other chemistries such as lithium-ion polymer, lithium sulphide and lithium tantalate cells are also being developed.[12] Thanks to their high energy density, lithium-based batteries are preferable to other types of cell; but they are also the most expensive format available.

Most forms of hybrid and fully electric vehicles realise efficiency gains through the use of regenerative braking, a process whereby the unused kinetic energy of slowing down the vehicle is converted back into electrical energy in order to recharge the battery. This is possible because electric motors can be inverted to operate as generators.[13] By recapturing up to 50% of braking energy, regenerative braking is said to increase efficiency by about 20% (MacKay, 2008).

3.2.1 Opportunities

The CO_2 reduction potential of vehicle electrification is best illustrated by the ladder of electrification/hybridisation (cf. BCG, 2009; E4tech, 2007; CCC, 2009a):

1) *Micro hybrid.* Micro hybrids include 'Stop & Start' and 'Stop & Go' systems. While Stop & Start systems shut down the engine when the vehicle stops and uses energy stored in the battery to start it again, in Stop & Go systems braking energy can be recovered and stored to start the vehicle again. Both systems help to reduce the energy lost through idling, and require only a small battery with 2-3 kWh capacity.[14]
2) *Mild hybrid.* While incorporating the above systems, mild hybrids are the first step to include regenerative braking and acceleration assistance for a slightly downsized ICE, and therefore require slightly larger batteries with 10 kWh capacity.
3) *Hybrid electric vehicle (HEV).* HEVs comprise all the features of the first two systems, but are also capable of pure electric drive at low speeds for a limited range, requiring stronger batteries with up to 30 kWh capacity depending on the size of the vehicle. The three main systems are:[15]
   i) *Parallel hybrids.* In parallel hybrid systems, the powertrain can be driven either by a downsized ICE or the electric motor, or even by both at the same time through the use of differential gears. When the performance load is low, the excess power of the ICE is used to recharge the battery via an alternator; when it is high, the ICE will be assisted

[12] SHIFT 2009, CIR conference, 3 December 2009.

[13] In the case of lead acid batteries, regenerative braking is only possible if used in tandem with an electricity storage device such as supercapacitors.

[14] Examples include the VW Lupo, which the manufacturer claimed has a fuel consumption of 3 L/100km, and the Citroën C3.

[15] The most prominent example of the full HEV is the Toyota Prius, the latest buyable generation of which can achieve a fuel consumption of about 4 L/100 km, and CO_2 emissions of 105 gCO_2/km or 30% less than the average new UK car (MacKay, 2008).

by the electric motor which is run by the energy stored in the battery.

ii) *Series hybrids.* In series hybrids, a downsized ICE turns a generator to produce electricity, which is then used to charge the battery or power the electric motor that drives the powertrain directly. This form of hybrid is also known as a Range-Extended Electric Vehicle (RE-EV).

iii) *Mixed hybrids.* These systems combine both the parallel and series systems in a complex architecture (e.g. a power split transmission).

4) *Plug-in hybrid electric vehicle (PHEV).* PHEVs have both an ICE and a battery with up to 40 kWh capacity, preferably lithium-based, that can be charged by the ICE or directly from the grid. They are able to run on electric drive up to approximately 50 mph for a range of anything between 5 to 50 miles depending on battery capacity.[16]

5) *Battery electric vehicle (BEV).* BEVs, commonly simply referred to as (full) electric vehicles (EVs), are propelled solely by an electric motor which runs on a battery charged entirely by electricity from the grid. As there is no ICE, BEVs are best equipped with powerful lithium-ion batteries (anything from 16 kWh upwards depending on the size of the car) which can make up about half of vehicle production costs.[17]

The efficiency savings and costs per vehicle are illustrated in Table 3. As can be seen, each further step requires more powerful and more sophisticated battery technology, the implications of which are threefold: vehicles become more expensive; vehicles become heavier, thereby partly offsetting efficiency gains; and CO_2 reduction potential increases.

Table 3 Hybrid and EV efficiency savings and costs

Vehicle type	Efficiency gains/CO_2 saving (%)	Cost per vehicle (£)
Micro	3-9 (higher figure with regenerative braking)	100-450
Mild	10-35	1,000-1,500
HEV	25-50	2,000-4,000
PHEV	>50 (depending on grid carbon intensity)	6,500 (35 km electric range) – 25,000 (350 km electric range)
BEV	40-100 (depending on grid carbon intensity	Cf. PHEV

Source: figures based on HM Treasury (2007); BCG (2009)

16 An example of a PHEV is the GM Volt (US)/Vauxhall Ampera (EU) which will be available in showrooms in 2011. The manufacturer claims that it will have an electric only range of 40 miles; it is expected to cost $40,000 in the US.

17 The showpiece of BEVs is the Tesla Roadster, a high-power car based on the Lotus Elise, which was recently launched in the UK. The most prominent niche vehicle to date is the G-Wiz, which is now available with lead acid and also lithium-ion batteries. BEVs that will be available in showrooms soon include the Nissan Leaf, Peugeot Ion/Citroën C-Zero and the Mitsubishi i-MiEV, all of which will run on lithium-based batteries.

From a tank-to-wheel perspective, grid-connected EVs (i.e. PHEVs on electric drive and BEVs) emit zero pollutants. In urban areas this is extremely beneficial as it will help reduce air pollution, which is estimated to cause 35,000 to 51,500 premature deaths in the UK, and costs up to £20 billion a year in terms of ill health and time off work (Marszal, 2010).

Theoretically grid-connected EVs could be carbon-free on a well-to-wheel basis provided they run on electricity generated from nuclear power plants or renewable energies such as wind, tidal and solar. This is a clear advantage over conventional vehicles which will always lead to the direct release of CO_2 through the combustion of hydrocarbon fossil fuels.

It is worth noting that all forms of electric vehicles will benefit also from advances in conventional vehicle systems. This not only includes improvements to ICEs which will benefit hybrids, but also reductions in vehicle weight and drag as described in the previous section.

3.2.2 Challenges

There are, however, four main challenges for vehicle electrification which relate more to grid-connected EVs.

The first challenge concerns battery technology and its costs. Currently, the production of a lithium-ion battery costs in the order of $1,000/kWh (roughly £650) (CCC, 2009a). Manufacturing the battery for a small PHEV/BEV (roughly 16 kWh) with a range of 90 miles will thus cost over £10,000, leading to very high purchasing costs. The high production costs are explained mainly by the complex manufacturing process and current 'diseconomies' of scale, i.e. production in comparatively small numbers. In order for BEVs/PHEVs to be able to compete with their ICE counterparts it is estimated that these costs will have to drop by a factor of four to about $250/kWh as aimed for by the Association of European Storage Battery Manufacturers (RTD Committee, 2005). Although the production cost curve for lithium-based batteries shows a downward trend in recent years (CCC, 2009a: 203), it is unclear how soon and how far costs will drop. While part of the cost reductions will certainly be achieved through large scale production, technological breakthroughs are also likely to be needed to push prices down to the required levels.[18]

The total costs of ownership are even higher when considering the relatively short lifespan of batteries. Batteries are fragile and prone to wear and tear, for example, if treated incorrectly through premature charging. Over time, all batteries lose capacity until they are no longer fit for use in vehicles (at 80% of original capacity).[19] In optimal conditions, batteries are assumed to have a lifespan six to eight years, which is likely to increase as the technology improves.

[18] The Future of the Automotive Powertrain within a Rapidly Changing Global Environment, IMechE lecture, 29 October 2009.

[19] Electric Vehicles at the Crossroads: Towards a Comprehensive EU-Wide Approach, AWBriefing conference, 18 February 2010.

Performance issues further compound the cost challenge. Owing to capacity constraints, full EVs offer only a very limited range compared to their ICE counterparts. According to manufacturers, today this is in the order of 60 to 100 miles for an affordable family car, which is far less than the range offered by conventional cars. Although a range of 100 miles would cover 96% of trips or 73% of aggregate car kilometres (CCC, 2009a), people have become accustomed to the range offered by conventional ICE vehicles. This means that potential users are likely to exhibit 'range anxiety' as they fear that full electric vehicles will not be able to meet their demands. The 'usable range ratio', i.e. the ratio of the vehicle's physical range to the range used by the user, is 2-3 times higher, meaning that the range is actually halved after factoring in range anxiety (ibid.).

The second challenge relates to infrastructure. Although grid-connected EVs can be charged by ordinary household sockets, a widespread uptake of these vehicles will require public charging infrastructure not only to be able cope with actual range constraints, but also to provide users with the psychological reassurance they need to overcome range anxiety. Whilst full recharging from households is slow and can take up to ten hours or 80% within two hours, thanks to higher amperage rapid charging points are able to recharge batteries up to 80% within 30 minutes or less. Deploying public charging infrastructure is, however, expensive and can cost up to £40,000 per fast-charging point, and another £50,000 if modifications to the local grid are required due to the high load (ibid.). The CCC therefore estimates that introducing the necessary charging infrastructure for the UK will be in the range of £150 million to £1.5 billion; while the lower estimate assumes simple off-street charging only, the higher estimate assumes a greater rollout of dedicated off-street charging, including fast-charging infrastructure.

Although the UK grid was designed to be able to cope with temporary overloads, a widespread uptake of grid-connected EVs could overburden the grid, for example when a large number of users recharged their vehicles at peak times (around 7pm). Whilst this problem can be mitigated to a certain extent through better electricity demand management, significant investments in grid infrastructure are likely to be needed if there is a large-scale rollout of public charging infrastructure. Furthermore, there can be the practical challenge for vehicle owners of accessing parking facilities with a charging point. Without the appropriate public charging infrastructure in place, people will have to resort to private parking facilities to charge their vehicles, which only 40% of city households – where an uptake of grid-connected EVs is expected to commence – have access to (ibid.).

A possible alternative to the system of charging points is the Better Place project, which is currently being rolled out in Israel and Japan.[20] Better Place provides automated swapping stations in which empty batteries can be exchanged with charged batteries

[20] For more information cf. http://www.betterplace.com/

within a matter of minutes. The system's advantage lies in the fact that it could largely eliminate problems regarding capacity constraints of the battery and thereby mitigate range anxiety, resolve parking issues, and match charging time to that of fuelling an ICE vehicle. Apart from the significant costs involved it would, however, also require a degree of standardisation in terms of battery size, chassis and mounting systems, which might take away manufacturers' competitive advantage in terms of battery and vehicle development.[21]

The third challenge for grid-connected EVs is environmental in nature. Whereas ICE vehicles' emissions occur at the 'wheel', PHEV/BEV emissions mainly occur at the 'well', as the majority of UK electricity is generated from burning carbon-intensive fossil fuels; in 2008, the share of carbon-free sources of electricity generation was only 18.5% (13% nuclear plus 5.5% renewable sources) (DECC, 2009). Today, the grid carbon intensity, measured in grams of CO_2 per kWh (gCO_2/kWh) generated 'at the plug', averages approximately 550 gCO_2/kWh, which includes 10% transmission losses.[22] If nominal performance figures are correct and BEVs use about 15 kWh/100km (MacKay, 2008), they will even on the current mix emit about 82.5 gCO_2/km or 45% less than the average new UK ICE-powered car. If, however, real world performance differs markedly from manufacturers' claims this figure could be in the same order as that of ICE vehicles.

The more important point, however, is the carbon footprint of electricity on the margin. In other words, it is the CO_2 emissions arising from one extra unit (e.g. kWh) of electricity generated that is of interest. A widespread uptake of BEVs and PHEVs could entail a sharp increase in electricity demand at peak hours as described above, and it is this extra demand that could drive up CO_2 emissions. This is because meeting it is likely to involve the burning of comparatively abundant fossil fuels, most notably gas, which is all the more true if other sectors of transport (e.g. rail) and the economy (e.g. heating) are also electrified.[23]

The other environmental problem is related to battery waste. While there is some uncertainty about the carbon-intensity of producing a battery pack, it is not entirely clear what will happen with batteries once they fall below the 80% capacity threshold and are no longer fit for use in vehicles. Even though parts of the battery are recyclable[24], some

[21] Shaping a Greener Future, Decarbonising Road Transport in the UK, AWBriefing seminar, 15 October 2009.

[22] A live update can be found at http://www.ecotricity.co.uk/about/live-grid-carbon-intensity and http://www.realtime carbon.org/

[23] It is hoped that electricity demand will be managed through Smart Grids and better demand management. Part of this could be vehicle-to-grid (V2G) or vehicle-to-home (V2H) systems, whereby electricity from batteries is fed back into the grid or home when unused.

[24] Modec, for example, a UK based manufacturer of commercial electric vehicles, are equipping their vehicles with lithium-sulphide batteries that do not use cadmium and are therefore biodegradable (SMMT International Automotive Summit, 24 November 2009).

components will not be recyclable, and will need to be disposed of. Short battery lifespans will inevitably increase waste, although this problem will be minimised through second-life applications such as electricity storage.

In terms of geopolitics, there is the risk of solving one problem by creating another: while an uptake of battery-based vehicles would certainly help society to break away from its dependency on oil, it could create new dependencies on lithium and so-called 'rare earths', which are certain scarce elements necessary for the manufacture of electric motors (e.g. magnets). In fact the Chinese government recently published its Rare Earths Industry Development Plan 2009-2015 in which it announced a cap on exports of rare earths (for which it has a global production monopoly) at the current level of 35,000 tonnes, and even considered a complete ban (Mason, 2009).

The final barrier relates to safety issues, both in terms of technological hazards and wider traffic safety. On the technological side, there are concerns about the hazardous material contained in batteries, particularly lithium, which may pose risks in the event of a collision. Contact with electricity also leads an element of risk: supercapacitors, for instance, have an elementary voltage that at several thousand volts far exceeds the lethal level of about 100 volts.

Regarding wider traffic safety, a study undertaken by the University of California suggests that at low speeds of around 20 mph, hybrids and full EVs need to be 40% closer to pedestrians and cyclists than ICE vehicles to be heard (UCR, 2008), thereby potentially constituting a greater safety risk for the elderly and those with impaired hearing or visual disabilities. This might well be the case in urban areas where 87% of traffic is below 25 mph (DfT, 2009c).[25]

3.2.3 Government policy

The UK government has recently developed a keen interest in advancing and promoting grid-connected EVs starting with the publication of the King Review and its future vision on the electrification of transport.

This is reflected in the fact that well over half the £400 million committed for low carbon vehicles will be used for the promotion of PHEVs and BEVs (DfT, 2009e):

- £230 million administered by the DfT as an incentive package for PHEVs and BEVs which will be handed out from 2011 to 2014 to encourage consumers to purchase these vehicles.
- £20 million for the investment into charging infrastructure through the Plugged-In Places Infrastructure Framework, complemented by £10 million from the low carbon element of the Strategic Investment Fund.

[25] Figure relates to the ten largest cities in the UK.

In order to meet its recommended targets, the CCC (2009a) has suggested that even stronger incentives might be needed during the early phase of introduction such as £10,000 per vehicle for the first 25,000 BEVs/PHEVs sold. It has also suggested that spending be increased to £800 million, meaning that total price support for 1.7 million BEVs/PHEVs in 2020 would be up to £9 billion.

A number of cities and regions are already involved in the promotion grid-connected EVs. In May 2009 the Mayor of London published his Electric Vehicle Delivery Plan in which he set out his vision to make London the electric vehicle capital of Europe (GLA, 2009). The £60 million plan covers three main aspects: it is intended that 25,000 charging points are rolled out by 2015; in terms of vehicles, the Mayor envisages to put 100,000 EVs on London's streets as soon as possible, and to increase the share of EVs in the whole Greater London Authority fleet to 1,000 by 2015; and EVs are to be promoted through several incentives, such as free parking and continued exemption from the London Congestion Charge (worth up to £1,700 per year).

3.3 Alternative fuels

The third principal way in which vehicles can be decarbonised is through the use of alternative fuels. This section will discuss the relative environmental merits of utilising biofuels and of moving towards hydrogen-based vehicles.

3.3.1 Biofuels

Biofuels are liquid fuels made from plant materials which can be used in internal combustion engines. They can be grouped into two categories: conventional and advanced biofuels. Conventional biofuels (or first generation) are produced from food crops including corn, sugar and vegetable oil, through processes such as fermentation (the conversion of carbohydrates into alcohols in the absence of air). Advanced biofuels, on the other hand, are produced from agricultural waste and residues (second generation) or algae (third generation). Production processes include for instance anaerobic digestion, where animal and food wastes are used to produce biogas which can then be upgraded to biomethane for use in motor vehicles.

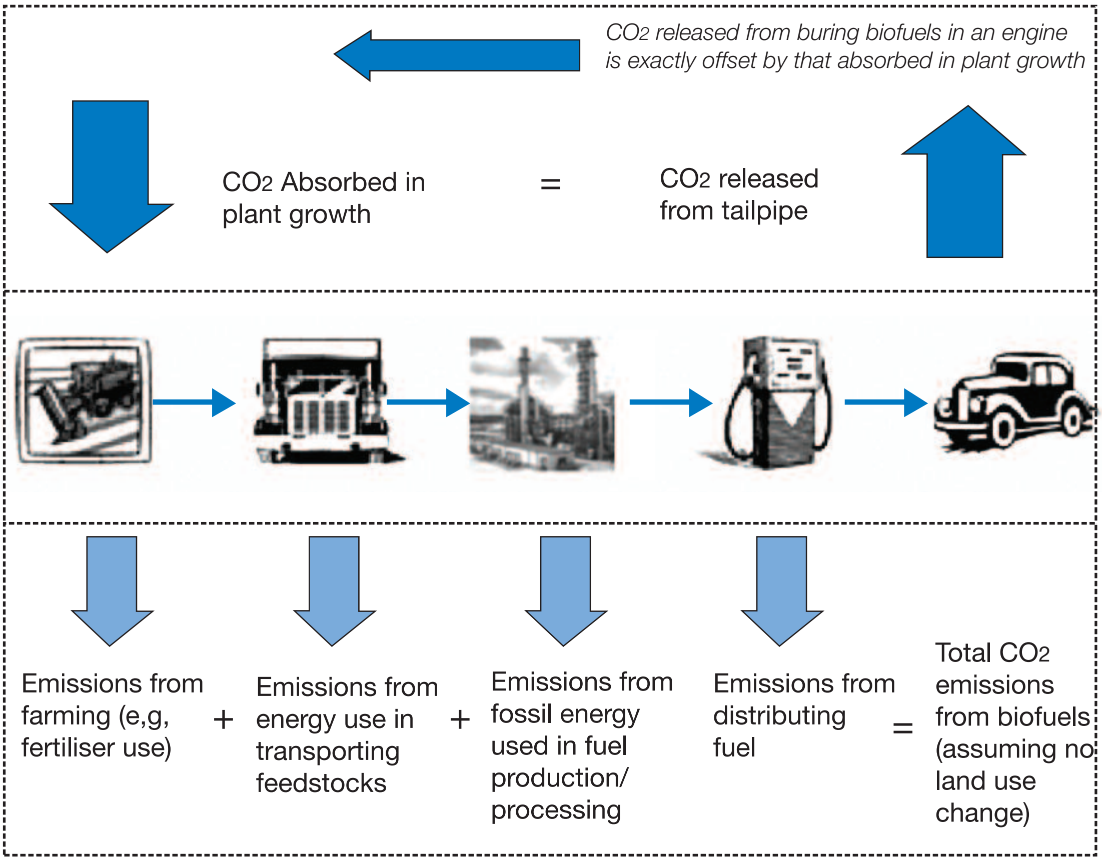
In the UK, the main biofuels are bioethanol and biodiesel which can be added to conventional fossil fuels at levels of up to 5% without any engine modifications. These fuels increase the oxygenate levels of petrol and diesel and so improve the combustion process (ibid.). Theoretically, most cars could run on 10% biofuel blends without any engine modifications, as found in the US.

Blends with over 10% biofuel content require modifications to the engine, for example recalibration, re-mapping and the use of different components, and/or the use of additives such as levulinic acid ethyl ester. Very high blends such as E85 (85% ethanol and 15% petrol) or E100 (100% hydrous alcohol) which can be found in the US and Brazil respectively, require so-called flex-fuel vehicles. The main difference between conventional and flex-fuel vehicles is a sensor that regulates the biofuel-fossil fuel ratio in the tank, and modified fuel tanks, including fuel lines and injectors made of non-corrosive material such as stainless steel and Teflon (ibid.).

3.3.1.1 Opportunities

From an environmental perspective, the problem with fossil fuels is that when burnt the CO_2 amassed over millions of years that would normally have been safely stored underground is released. Biofuels are inherently different. Even though CO_2 is released as they burn (but less so than compared with fossil fuels), they can make a contribution to reducing GHGs because they have absorbed CO_2 through photosynthesis in their lifetime, thus making a complete cycle as illustrated in Figure 4:

Figure 4 GHG reductions from biofuels



Source: HM Treasury (2007)

Table 4 GHG balance of conventional biofuels

Type of biofuel	Well-to-tank emissions (gCO_2/km)	Reduction in GHG emissions (%)	Further explanation
Ethanol from sugar cane	20	80 (compared with petrol)	N/A
Ethanol from sugar beet	58	64 (compared with petrol)	Pulp used for process heat
Ethanol from sugar beet	111	32 (compared with petrol)	Pulp used for animal feed
Ethanol from wheat*	49-114	7-77 (compared with petrol)	The wide range depends on the production process used and the use of co-products
Ethanol from lignocellulosic biomass	10-40	73-94 (compared with petrol)	Emissions vary depending on feedstock
Biodiesel from rapeseed	83 (average)	46-53 (compared with diesel; 38% if used for animal feed, 57% if used for energy)	Figures based on conventional base catalysis. Savings vary depending on whether rape meal is used for animal feed or for energy.
Syngas derived biofuels	9 (estimate)	94 (compared with diesel)	Early technology status means only estimates are currently available

* For a more detailed calculation of well-to-wheel emissions for Ethanol from wheat please see LowCVP (2004)
Source: E4tech (2007)

Table 4 illustrates the GHG balance of conventional biofuels.[26] Although figures vary, it is clear that biofuels can offer considerable GHG savings depending on the production process and other aspects such as transportation and the cultivation of crops.

A specific advantage of biofuels over grid-connected EVs is that mass market commercialisation is not so dependent on niche markets. This is mainly due to the infrastructure required for biofuels being very similar to that already used for petrol and

[26] For a comparison of the figures please cf. Annex V A. and B. of EU Directive 2009/28/EC available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF. Although exact figures differ, they are generally in the same order of magnitude.

diesel, although modifications to ensure that ethanol is not mixed with water would be required. Furthermore, while blends of 5% require no engine modifications at all, even 10% biofuel blends will require only slight engine modifications (e.g. recalibration and re-mapping) (ibid.).

According to the Low Carbon Vehicle Partnership (2009), a penetration of 5% biofuels into the total UK car fleet could reduce annual GHG emission by between 0.5 to 2.2 $MtCO_2e$ depending on the type of biofuel.

3.3.1.2 Challenges

The first challenge to biofuels becoming part of a low carbon vehicles future is their cost and commercial availability. Whilst some conventional biofuels are commercially available, they are still not cheap enough to be able to compete with conventional fossil fuels without government support. Depending on the production pathway, conventional biofuels are at least 50% more expensive than petrol or diesel (E4tech, 2007).

In contrast, despite the potentially greater GHG savings and minimisation of indirect effects, advanced biofuels are not yet commercially available because of their technical immaturity and high production costs. Uncertainty surrounding these types of biofuel creates a ‘chicken and egg’ problem because potential operators face a market risk in investing in high capital cost mass scale production facilities which are needed to recover investment (ibid.).

A more critical challenge for conventional biofuels specifically, is the ‘food versus fuel’ conflict. Although this tension touches upon many aspects (e.g. extreme weather conditions, food markets distorted by subsidies), the underlying economic logic is nevertheless simple. Arable land is finite, and food crops are scarce. As demand for biofuels increases and more of the finite land is used for biofuels production, the share of land for food production decreases. This will cause food prices to rise if demand exceeds supply, adversely affecting the poor. In fact, this conflict could be seen as one of the causes of the Mexican food price hike in 2008 where increasing US demand for corn-based ethanol impacted upon tortilla flour prices (cf. CCC, 2009b).

While it is true that Malthusian theory[27] did not hold true over the past half century thanks to increases in agricultural productivity, it is uncertain whether progress will continue at a pace that is needed. This is because the increased productivity of the mid-20th century was possible mainly through the use of energy-intensive fertilisers and of water, the use of which will become increasingly constrained by concerns over climate change. The government estimates that in 2050 demand for water in the UK will be 30% higher than today, which will limit its availability for agricultural use (ibid.). The availability of marginal land is further limited by projections that the global population will increase sharply from 6.7 billion today to 9.1 billion in 2050 which according to the CCC, will increase the demand for food by 70%.

[27] The 18th/19th century economist Thomas Malthus predicted that while food supply would grow linearly, population would grow exponentially, thereby creating food shortages and famines.

Significantly, these pressures do not take into account increasing demand for resource-intensive commodities such as transport as countries get richer.

There are also concerns regarding the environmental impact of conventional biofuels as their GHG savings may be heavily offset due to the energy that is required for the cultivation, harvesting, processing and transportation of biofuels. More importantly, they may cause direct and indirect land use change (RFA, 2008). The former occurs where growing feedstock for biofuels results in deforestation or conversion of land, both of which release CO_2 into the atmosphere that would otherwise have been stored in the trees or soil. Indirect land use change, on the other hand, occurs where growing feedstocks for biofuels displaces food production, resulting in deforestation, conversion of carbon-rich soils, or the cultivation of less productive land requiring more energy-intensive fertilisers. Complex supply chains make estimates of the net lifecycle impact of indirect land use change highly uncertain, but it has been calculated that the use of energy-intensive fertilisers alone can offset GHG savings by 50 to 80% (CCC, 2009b). Furthermore, land use change may also lead to species and biodiversity loss through habitat destruction and the encouragement of mass-scale monocrops that erode biodiversity.[28]

Given their scarce nature, biofuels come at a comparatively high opportunity cost which raises the question as to whether they are better used in other sectors of the economy where they might offer better value for money or where there are fewer alternatives to existing technologies. While biomass (which can be processed into biofuels), for example, can be used in combined heat and power plants or co-firing with coal using carbon capture and storage technology to decarbonise electricity, two-thirds of world global supply are actually used as a primary energy source for cooking and heating in developing countries (ibid.). Using biomass from overseas will therefore conflict with these other important needs. Even when produced entirely domestically in the most sustainable way, there are uses of biofuels, most notably aviation and shipping, where there will be no other viable alternative to liquid/gaseous fuels, and demand is expected to increase in the next decades (ibid.).

3.3.1.3 Government policy

In the UK, biofuels are governed by the Renewable Transport Fuel Obligation (RTFO)[29] which implements the targets and aims of the EU directive on the promotion of biofuels and other renewable transport fuels.[30] The directive stipulates that across the EU 5.75%

[28] A case in point is palm oil production in South East Asia, which in 2007 accounted for almost a third of the EU's palm oil imports, and is expected to increase owing to growing demand for biofuels. Vast areas of Malaysia and Indonesia have been deforested for growing oil palm trees on monoculture plantations, which has caused biodiversity loss and the immediate release of CO_2 (European Commission, 2007).

[29] http://www.opsi.gov.uk/acts/acts2004/ukpga_20040020_en_12

[30] Directive 2003/30/EC available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:123:0042:0042:EN:PDF

of fuels shall be sourced from renewables in 2010, with a longer-term target of 20% in 2020; the individual target for the UK being 15%. In order to ensure compliance, the directive requires EU member states to report to the European Commission on their progress towards meeting the targets.

In effect, the RTFO functions much like a cap-and-trade system. Certificates are given to fuel suppliers who comply with the standards by reporting to the Renewable Fuels Agency (RFA) set up under the obligation: suppliers who exceed the targets can sell their surplus certificates to those who do not comply; non-compliers can alternatively choose to pay a 30 pence per litre fine (from 2010), which is set at a level to discourage non-compliance and to stimulate an increased uptake of biofuels. However, by setting targets merely for volumes and by not including sustainability and GHG criteria, the RTFO did not further the development of advanced biofuels.

Following concerns regarding the sustainability of biofuels, in 2008 the UK government commissioned the Chair of the RFA, Professor Ed Gallagher, to review the indirect effects of biofuels production (RFA, 2008). The review's main message was that to ensure sustainable development, a slowdown in the growth of biofuels was needed through setting lower targets. Recognising the imperative of eliminating the impact on food supply and to avoid environmental impacts from indirect land use change, it advocated incentives for the production of advanced biofuels and use of idle and marginal land through mandatory sustainability standards for fuel suppliers.

Taking the advice of the Gallagher Review, the UK government lowered the target set out by the EU through the RTFO to 3.25% in 2010, with a gradual increase to 10% in 2020. In addition, the Government announced in its Budget 2008 that the 20 pence per litre tax incentive for biofuels would be removed from April 2010 (with the exception of biofuels produced from waste cooking oil, which will continue for another two years). Graduated vehicle excise duty, which offers lower tax payments for cars running on alternative fuels will remain, however.

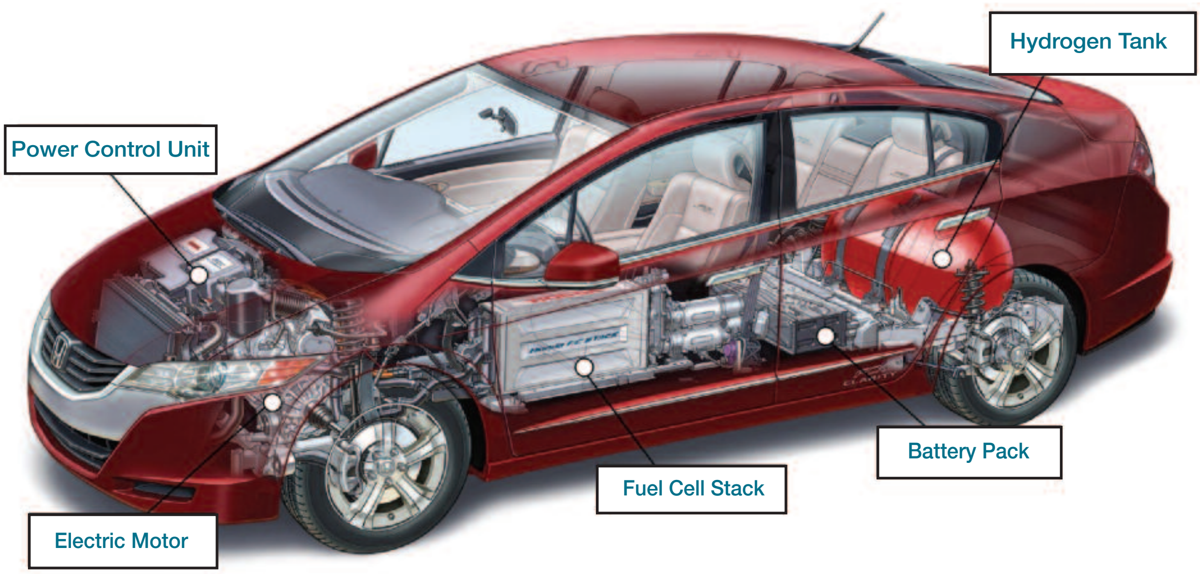
Meanwhile the EU adopted a new Directive on the promotion of renewable energies.[31] This directive amends that of 2003 and will take effect in 2012 to incorporate mandatory sustainability criteria (such as direct and indirect land use change, deforestation and biodiversity) and minimum GHG standards to encourage an uptake of advanced biofuels. Under the directive, GHG emission savings shall be at least 35% from 2012, 50% in 2017 and 60% in 2018. Moreover, fuel suppliers will no longer be able to report 'unknown' biofuel origins, something which is permissible under the current scheme because of the difficulty of obtaining this information; suppliers are now aided by default values on GHG savings and detailed guidance on how to calculate them for different production routes.

[31] Directive 2009/28/EC available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF.

3.3.2 Hydrogen

Hydrogen (H_2) can be used either in modified ICEs or in combination with a fuel cell (Figure 5), either in gaseous or liquid form. A hydrogen ICE effectively functions like a spark ignition ICE but requires alterations so the hydrogen can be combusted. Fuel cell vehicles, on the other hand, function as follows: hydrogen is fed into the anode (negative electrode), after which the molecules are split into electrons and protons with the help of a catalyst; the electrons are channelled through a circuit to generate electricity; protons pass through the electrolyte membrane; oxygen enters the cathode (positive electrode) and combines with the electrons and protons to form water and heat. The electricity is stored in a battery which powers an electric motor.

Figure 5 Fuel cell vehicle



Source: Honda UK (2010)

Unlike some other gases, hydrogen does not occur freely and so must be produced. There exist many different production paths, all of which are different in terms of their energy consumption and costs. Currently the most common form of large scale production is steam reforming of hydrocarbons, i.e. natural gas or even coal, which essentially involves splitting the steam (i.e. H_2O) into its components. The hydrogen produced is almost entirely used as industrial gas, rather than as an energy carrier.

Other production pathways include: nuclear or central wind electrolysis whereby water is decomposed into oxygen and hydrogen by an electric current that passes through the water; thermal decomposition where water is heated up to very high temperatures and splits into its chemical components; chemical production in which various materials react with water or acids; and fermentation, where biomass is converted into hydrogen using bacteria, enzymes and anaerobic conversion.

3.3.2.1 Opportunities

From an energy efficiency perspective, hydrogen fuel cell vehicles outperform conventional vehicles. Current fuel cells can achieve efficiencies of up to 60% (e.g. the Honda FCX Clarity according to the manufacturer; Honda, 2010), which is much higher than the 20-40% achieved by ICE vehicles.

In fact hydrogen may be viewed as the ultimate form of low carbon vehicle technologies (or any technology that relies on the use of energy for that matter) simply because the only waste product that occurs when reforming is water and heat (US DoE, 2010c); if produced sustainably, hydrogen can offer substantial well-to-wheel GHG savings. Zero tailpipe emissions also contribute to improved local air quality as described in section 3.2.1.

In terms of practicality, hydrogen vehicles offer several specific advantages over full electric vehicles. The first relates to range. Although fuel cell vehicles do not deliver the same range as conventional cars, they can reach up to 300 miles (ibid.), which is about three times as much as the average range of a battery electric vehicle. This means that hydrogen fuel cell vehicles are not restricted to use in urban areas, but can be employed for longer trips. Secondly, as with conventional cars, refuelling only takes a couple of minutes and so does not require designated parking spaces or long charging times. Both factors combined are less likely to cause range anxiety. Finally, hydrogen can power heavier cars more easily, which is more in line with the conventional car paradigm.

Because hydrogen can be produced from many different energy sources, it could break oil dependency and contribute to energy security.

3.3.2.2 Challenges

Although technologies for the compression, liquefaction and transport of hydrogen are used in the industrial gas sector, a number of difficulties make a widespread and sustainable uptake of hydrogen in the personal transport sector unlikely in the near future. These barriers can be grouped into three categories, with costs constituting a fundamental challenge for each: vehicle technology, infrastructure and hydrogen production.

For hydrogen vehicles themselves, the challenges are twofold: propulsion technology and onboard storage. In terms of propulsion, both forms of hydrogen vehicle must overcome certain technical, as well as cost, barriers. Whilst the technical issues for hydrogen ICEs relate to fuel injection at very low temperatures, improved combustion efficiency and leak detection (E4tech, 2007), fuel cells for automotive application face more complex challenges regarding power density, reliability and durability, as well as performance in extreme environments (such as subzero temperatures where a fuel cell's internal water environment can freeze) (US DoE, 2010c). Fuel cell costs must drop from $51/kW to $30/kW if vehicles are to become competitive with conventional cars (ibid.).

In its gaseous form, hydrogen has a low volumetric energy density (megajoules per litre) in ambient conditions, which causes storage tanks to be heavy and to require more space than petrol or diesel tanks. Current costs of $15-18/kWh must be reduced to $2/kWh to become commercially competitive. Liquid hydrogen, on the other hand, has a high density but is thirty times more expensive than hydrogen gas and suffers from safety and performance problems (ibid.).

Like any other low carbon vehicle technology, hydrogen vehicles require a refuelling infrastructure. Although hydrogen refuelling equipment is relatively mature thanks to its industrial application, it is costly to put in place for automotive application. According to modelling by the Policy Studies Institute (2008), cumulative costs for hydrogen provision until 2050 to meet an 80% GHG reduction target could amount to billions of pounds (the model assumes that in an 80% GHG reduction scenario by 2050, over half of transport would be fuelled by hydrogen).

Finally, there is the challenge of producing hydrogen for use in vehicles that is both sustainable and cost-effective. Most production pathways that are commercially viable and available today are found in industrial applications and involve the reforming of hydrocarbons (most notably gas) which releases direct CO_2 emissions into the atmosphere. This could be reduced if carbon capture and storage (CCS) technology is employed, but uncertainty remains as to the economic viability and deliverability of CCS.[32]

Overall there is uncertainty surrounding a rollout of hydrogen vehicles. As with grid-connected electric vehicles, it is unclear how the simultaneous development of infrastructure, renewable hydrogen and provision of vehicles at an economically viable rate will be achieved. This uncertainty is partly due the fact that there are no hydrogen vehicles available in UK showrooms today.

32 Carbon Capture and Storage - next steps: finance, demonstration and feasibility, Westminster Energy, Environment & Transport Seminar, 23 October 2009.

3.3.2.3 Government policy

Given the current stage of development of hydrogen as a fuel for automotive applications, government activity is mainly focused on RD&D funding provided through Cenex, the DfT's Infrastructure Grant Programme and the Technology Strategy Board. The latter has in fact only recently announced a £7 million fund to accelerate the development and deployment of hydrogen and fuel cell technologies which companies will be able to bid for (TSB, 2010). The money will be made available to 15 demonstrator projects for transport and stationary market applications. Hydrogen fuel cell vehicles will also benefit from the £230 million consumer incentive package as outlined in section 3.2.3 (DfT, 2010).

London has been playing an important role in the promotion of hydrogen vehicles. Set up in 2002, the London Hydrogen Partnership (LHP, 2010) provides a central platform for stakeholders in the hydrogen sector, which aims at facilitating development and deployment of such technologies. As member of the Hydrogen Bus Alliance, Transport for London has participated in the Clean Urban Transport for Europe project which received £450,000 to test the first generation of fuel cell buses (TfL, 2010). It has been announced that a further 70 hydrogen vehicles, ten of which will be buses, will be deployed by the end of 2010 (ibid.), and that the Olympic Games in 2012 will be used as an opportunity to demonstrate hydrogen vehicles. In order to stimulate development, hydrogen demonstrator projects have in the past been exempt from fuel duty (E4tech, 2007).

In its move towards decarbonising the economy, the government recently set up six Low Carbon Economic Areas, each of which will focus on certain low carbon technologies. The one established in South Wales will specialise in hydrogen energy with the aim of creating an extensive hydrogen fuelling infrastructure and making the M4 the UK's first 'hydrogen highway'. As part of the project the University of Glamorgan will be investing £6 million into the development of hydrogen technologies (BBC, 2010).

4. Conclusions

This paper maps out the current developments in low carbon vehicle (LCV) technology and how they relate to government policy whilst identifying some of the key opportunities and challenges in bringing them to market with good prospects of widespread market adoption. In these conclusions we set out our preliminary views on these issues.

There is no single solution: All technological options offer opportunities but at the same time they face certain challenges; in some cases significant barriers:

- **For conventional cars and powertrains:** It is clear there remains significant scope for reducing the carbon emissions of vehicles with conventional powertrains. The main opportunities relate to engine improvements, weight reduction and downsizing alongside improved aerodynamic design. One of the major advantages over other LCV technologies is that improvements can be achieved at approximately £1,500 per vehicle which could pay for themselves through fuel cost reductions over three to five years. Moreover, all the necessary complementary technologies such as infrastructure and skills are already in place. There are, however, limits to how much can be achieved in terms of carbon dioxide (CO_2) savings. Further improvements will require changes in the vehicle purchasing decisions and driving style of consumers.

- **Electrification:** The use of electric power offers several advantages. Based on developments over the past ten years, hybrids, which combine an internal combustion engine (ICE) with the ability to capture and re-use energy electrically that would otherwise be wasted, present a good mix between conventional propulsion and battery technology. Carbon savings of up to 30-50% are achievable for approximately £2,000-4,000 per vehicle, and vehicles are very similar to conventional cars not restricted by range. Although grid-connected electric vehicles (plug-in hybrid vehicles on electric drive and battery electric vehicles) can potentially offer close to zero well-to-wheel emissions, depending on the carbon footprint of electricity generation, they still face substantial challenges relating to battery cost which currently makes them far more expensive than their ICE counterparts. This is even more the case if infrastructure costs are factored in. Decarbonising electricity generation and supply will pose a challenge for maximum CO_2 reduction.

- **Alternative fuels:** Biofuels, especially advanced ones which are produced from wastes and residues rather than food crops, potentially offer significant GHG savings when based on a complete life cycle, but only if they do not result in direct or indirect land use change or significant GHG emissions from cultivation and transport. Furthermore, questions remain about the opportunity cost of biofuels, for instance if they are better employed in aviation or other sectors of the economy rather than road based transport. Hydrogen vehicles offer zero tailpipe emissions and increased range, but are still at a relatively early stage of development. They have a number of technology and cost barriers to overcome, for vehicles, infrastructure and the actual carbon content of hydrogen.

The analysis of policy: The Foundation strongly recommends that policies are developed and strategies evaluated on well-to-wheel analyses, and preferably cradle to grave assessments that also take into account the energy required and CO_2 emissions created by manufacturing, distribution and eventual disposal or scrappage of vehicles. Until now, however, policies such as the EU Directive and UK tax incentives are based on tank-to-wheel/tailpipe emissions. This can distort decisions intended to reduce emissions over the long term.

Market demand: Central to achieving a widespread rollout of vehicles and efficiency improvements, is the demand and take up within the market place, as the automotive industry will only develop competitive alternatives if it anticipates sufficient return on investment. Government has a key role to play in encouraging demand through the adoption of fiscal incentives geared towards lower emission vehicles, subsidies for car purchase or for scrappage, grants for R&D and concept development, and grants for low carbon vehicle charging infrastructure.

It is still ‘early days’ for the adoption of new vehicle technologies by the public – even hybrids, available for over ten years, have only a small market share. The Foundation questions whether there is sufficient understanding of the factors that will drive market adoption of low carbon vehicles. Future research should focus on potential market behaviour and how it will respond to and be influenced by the emergence of these new technologies, as well as the continuous improvement of conventional powertrains.

The role of government: At this stage, the role of government is complex and subtle. Promising ideas should be encouraged without distorting the market or stifling market-led development, and policy decisions need to be taken not just at a national level, but on an international basis. It is also crucial that incentives aimed at encouraging take-up are financially sustainable and appropriate. The government’s recent commitment to substantial grant programmes supporting both consumer uptake of low carbon vehicles and the provision of a charging infrastructure for electric vehicles is an important start but with the scheme set to run only until 2014, subsequent plans to encourage take up will have to be considered carefully.

The RAC Foundation regards the greening of road transport as crucial for two reasons. Firstly so motorists can play their part in tackling climate change, and secondly to protect personal mobility which is so important to the economic and social wellbeing of the nation.

The challenge is not only to stimulate both the supply and demand side of the low carbon vehicle market, but to make sure progress on each happens in tandem. It will not be easy but it must be done.

Glossary

ACEA	European Automobile Manufacturers' Association
BERR	Department for Business, Enterprise and Regulatory Reform
BEV	Battery electric vehicle
BIS	Department for Business, Innovation and Skills
Cenex	Centre of Excellence for Low Carbon and Fuel Cell Technologies
CCC	Committee on Climate Change
CCS	Carbon capture and storage/sequestration
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DEFRA	Department for the Environment, Food and Rural Affairs
DfT	Department for Transport
EU	European Union
EV	Electric vehicle
GHG	Greenhouse gas
Gt	Giga tonnes
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
IEA	International Energy Agency
LCV	Low carbon vehicle
LHP	London Hydrogen Partnership
Mt	Million tonnes
NAIGT	New Automotive Innovation and Growth Team
PHEV	Plug-in hybrid electric vehicle

5. Glossary

R&D	Research and development
RD&D	Research, development and demonstration
RE-EV	Range-extended electric vehicle
TSB	Technology Strategy Board
TfL	Transport for London

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